Analytical and Experimental Investigation of Mixing in Large Passive Containment Volumes

3rd Year NEER Final Report

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This final report details results from the past three years of the three-year UC Berkeley NEER investigation of mixing phenomena in large-scale passive reactor containments. We have completed all of our three-year deliverables specified in our proposal, as summarized for each deliverable in the body of this report, except for the experiments of steam condensation in the presence of noncondensable gas. We have particularly exciting results from the experiments studying the mixing in large insulated containment with a vertical cooling plate. These experiments now have shown why augmentation has been observed in wall-condensation experiments due to the momentum of the steam break-flow entering large volumes. More importantly, we also have shown that the forced-jet augmentation can be predicted using relatively simple correlations, and that it is independent of the break diameter and depends only on the break flow orientation, location, and momentum. This suggests that we will now be able to take credit for this augmentation in reactor safety analysis, improving safety margins for containment structures. We have finished the version 1 of 1-D Lagrangian flow and heat transfer code BMIX++. This version has ability to solve many complex stratified problems, such as multi-components problems, multi-enclosures problems (two enclosures connected by one connection for the current version), incompressible and compressible problems, multi jets, plumes, sinks in one enclosure problems, problems with wall conduction, and the combinations of the above problems. We believe the BMIX++ code is a very powerful computation tool to study stratified enclosures mixing problems.

Passive containments, which use natural circulation to remove decay heat following an accident, provide the greatest promise for nuclear energy to repenetrate U.S. and European markets that have not seen new plant orders in two decades. The first plants reentering these markets will likely be LWRs, where proven reactor technology and licensing reduce financial risk. Innovative passive containments for these LWRs can provide strong public confidence in safety, as well as reduce plant cost (for a given reactor size).

INTRODUCTION

The principal purpose of the UC Berkeley NEER research is to improve understanding and modeling capabilities for mixing and heat/mass transfer to walls and structures in large containment volumes, as illustrated schematically in Figure 1. Two conditions are typically observed in such volumes, either a zero-dimensional well-mixed state where lumped treatment of the volume's mass and energy provides an accurate treatment of the conservation equations, or stratified conditions where substantial vertical temperature and concentration gradients may exist, particularly where mass may "hide out" in stagnant stratified regions, and where vertical transport occurs in relatively thin wall and free buoyant jets. In the second case substantial challenges exist to model the transport processes with three-dimensional codes, because the finite-difference treatments generate substantial artificial diffusion which smears greatly the sharp gradients that exist in physical systems. The UC Berkeley BMIX++ code approach uses integral models to treat the wall and free buoyant jets, allowing their detailed structure to be treated accurately, and one-dimensional Lagrangian modeling of the stratified ambient. We have demonstrated that this method can eliminate the effects of numerical diffusion, down to the numerical precision of computers used for the computation (Christensen and Peterson, 1999). We have also demonstrated excellent agreement between the numerical model and analytical and experimental data.

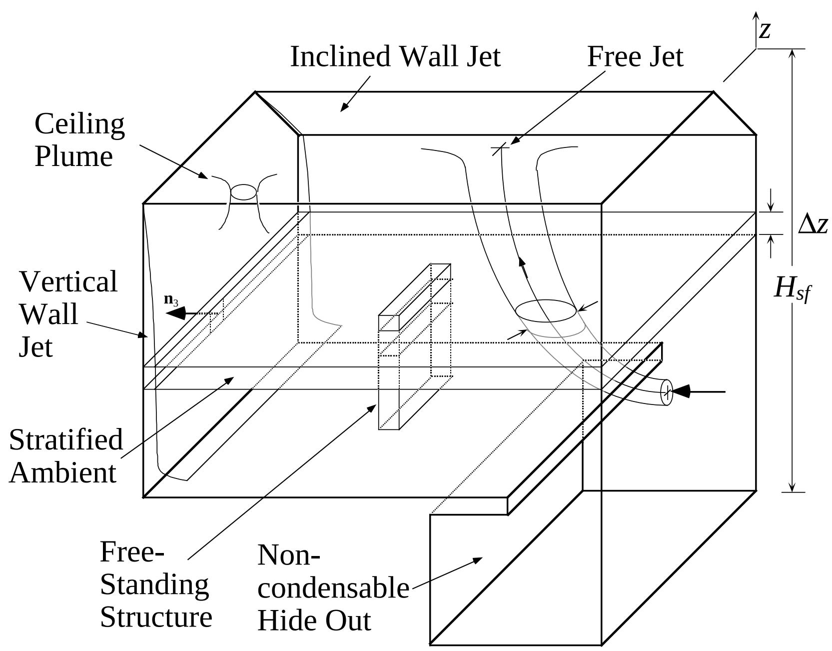

Fig. 1 Schematic of jet mixing processes in a large containment volume.

Currently two graduate students are working on the modeling and experimental efforts. A complete experimental system (Fig. 2) was constructed, including heating system, cooling system, test section with a large insulated rectangular enclosure, and measure system.

Fig. 2 Picture of Experimental System

FINAL DELIVERABLES RESULTS

Modeling Tasks

1) *Equations of State and Compressibility Effects (YEAR 1).*
   Deliverable: Conference/archival paper on topic of incompressible modeling of compressibility effects (quasi-steady modeling); summary of modeling method in annual progress report.

The paper describing the numerical implementation of the new computational approach, and comparisons with experimental and analytical predictions, was completed and presented at the NURETH-9 conference in San Francisco, and was accepted for archival publication in Nuclear Engineering and Design (Christensen and Peterson, 1999). The method to be employed to incorporate compressibility effects has also been developed. The important insight is that while unequal inflow and outflow from a volume can force compression of the gas in the volume, the flow is not compressible in the standard sense, and is best treated as a quasi-incompressible fluid where pressure signals transmit instantly and the fluid inventory compresses uniformly to accommodate inventory changes. To implement the solution numerically, the standard incompressible algorithm is used for each time step, so that inventory changes in the Lagrangian treatment cause the total volume of the system to change. A corrector step is then employed to correct the volume pressure to restore the correct total volume, changing the volume of each Lagrangian zone to reflect the equation of state of the gas species.

2) *Develop Library of Free-Jet Models (YEAR 1, 2, 3).*
Deliverable: Include models in relevant conference/archival papers; summarize new models in annual progress reports.

One of the doctoral students has completed a comprehensive survey of modeling methods for buoyant free and wall jets from literature from 1979 through the present. This student then developed a suite of integral models and coupled into the BMIX++ code.

3) *Develop Library of Wall-Plume Entrainment, Heat Transfer and Condensation Models (YEAR 1, 2, 3).*
Deliverable: Include models in relevant conference/archival papers; summarize new models in annual progress reports.

Boundary layer flow adjacent to isothermal surfaces, both laminar and turbulent flow, has been widely studied. Approximate integral analysis about laminar and turbulent flows used widely in fire analysis area has been coupled into the BMIX++ code.

4) *Coupling to Integral Thermal Hydraulics Codes (YEAR 2).*
Deliverable: Discuss effectiveness of coupling in relevant conference/archival papers; publish final code in final report and make available on web.

Due to the complexity of this target, we have postponed the study until we have fully tested our code.

5) *Algorithms for Multiple Large Volumes (YEAR 3).*
Deliverable: Include models in relevant conference/archival papers; summarize new models in annual progress reports.

We have finished the algorithms for multiple large enclosures problems. The key model for multiple enclosures calculation is opening model. Opening is simulated by pairs of jet and sink at the opening location. For small opening, the flow is always in one direction at a fixed time; while for large opening, the flow may not be unidirectional, i.e., there may be some gas flowing in and some flowing out of the enclosure. Mass flow through a vertical vent is driven by the pressure difference between the two sides of the opening, and it can be calculated by Bernoulli's equation along the flow direction. For large opening, the total cross section of the opening is divided into several parts, each part having the same flow direction. For any sub-divided part of a rectangular opening (slab), the formulation used by CFAST is used to calculate the mass flow rate. Pressure used for opening calculation is according to the energy conservation equation for the lumped compressible volume and hydrostatic pressure distribution. The pressure equation is solved by implicit scheme. The comparison with fire experiment shows that the algorithms can obtain favorable vent flow rate.

The paper(Zhao, Niu, and Perteson, 2002) describing BMIX++ code predictions for mixing and heat transfer augmentation in a large rectangular enclosure with an injected buoyant jet and a large, cooled vertical surface and some experiment result was presented at the ANS Annual Meeting, Session 4b (DOE-NEER), Hollywood, Florida, June 9-13, 2002. This paper describes our recently large rectangular enclosure mixing experiment and the overall BMIX++ code models. The predicted ambient mixing for the new experimental system was calculated using the BMIX++ code, including the effects of heat loss to the insulated walls. The density interface rapidly assumes a quasi-steady location that is governed by the competing effects of the hot buoyant jet, which entrains and transports fluid up to the ceiling, and the cold wall jet on the vertical cooled surface, which entrains and transports fluid down to the bottom of the enclosure. The predicted quasi-steady temperature interface in the stratified ambient, is observed in experiments, and provides an important and interesting validation case for the BMIX++ code.

Experimental Tasks

1) *Forced-jet augmentation of natural convection heat transfer.*
   Deliverable: Present experimental results and comparison to models in relevant conference/archival papers; publish experimental results in progress report and make available on web.

Four years ago we reported evidence from limited experiments reported in the chemical engineering literature on forced convection heat transfer induced in vessels by jet injection (Peterson and Gamble, 1998), that when presented in nondimensional form, the forced-convection augmentation of natural convection would take a very simple form. The potential for this result is important, since break flows in reactor containments have been postulated to be important sources of heat and condensation mass transfer augmentation. This effect, for example, was postulated as the reason for higher condensation mass transfer being observed in AP-600 containment condensation experiments than would be predicted by standard natural convection correlation for noncondensable gas effects (Woodcock et al., 1999). However, no information has been available to predict the augmentation effect, or to predict how it scales from test facilities to full-scale systems. Thus in addition to not being able to take credit for the augmentation effect, questions exist as to whether it is conservative to apply condensation results from scaled facilities, where augmentation is known to occur due to the momentum of the injected steam jet, to a full scale facility where the injected momentum may be larger or smaller.

We have obtained some experimental results in investigating the augmentation of heat transfer from the vertical cooling surface of a 2.29m×2.29m×2.29m enclosure where a hot air jet with varying momentum, diameter, and position is injected into the volume. We find that the augmentation depends basically on the direction of injection and on the Archimedes number (Re^2/Gr), and not directly on the Reynolds number or the diameter of the jet. This means that the heat transfer augmentation by injected jets can be bounded, and is relatively independent of the size of the enclosure when correlated by the Archimedes number. Fig. 3 illustrates jet position effect on mixed-convection augmentation of natural convection heat transfer. We can find the mixed-convection augmentation increases as the height of jet decreases. Since hot air is horizontally injected into the enclosure and forms a buoyant jet thereafter, lower jet position means better mixed ambient fluid, which will improve the convection heat transfer.

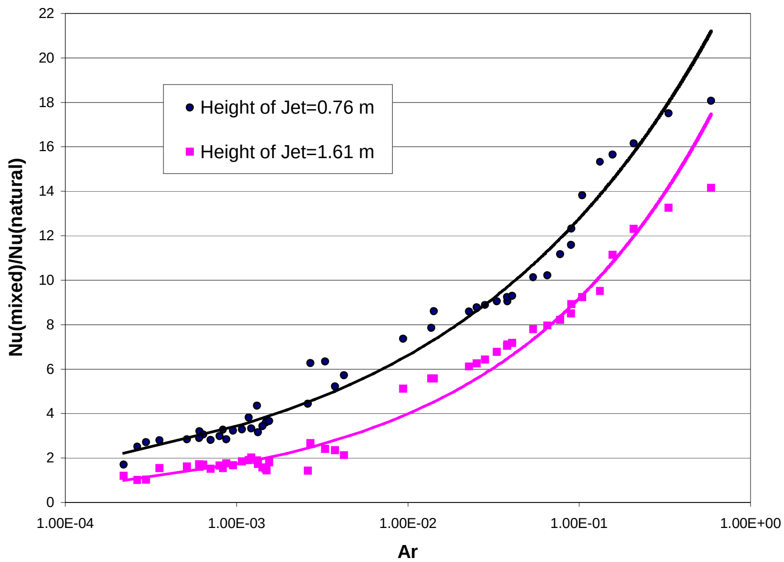

Fig. 3 Jet Position Effect on Mixed Convection Heat Transfer

2) *Effects of Varying Forced-Jet on Ambient Temperature Stratification.*
Deliverable: Present experimental results and comparison to models in relevant conference/archival papers; publish experimental results in progress report and make available on web.

Often strong stratification induced by temperature gradients is observed in large enclosures, where the temperature distributions become one-dimensional and can be modeled by simple governing equations. This allows very large reductions in computational effort compared to three-dimensional numerical modeling of turbulent mixing in large enclosures. The momentum injected by forced jets can potentially break down stratification in large enclosures. This experiment studies the bulk temperature distributions in the enclosure and tests the criteria for assessing when breakdown will occur. The corresponding paper “Experimental Investigation of Forced-jet Mixing and Augmentation of Natural Convection Heat Transfer in Large Stratified Volumes”(F. Niu, H. Zhao, and P.F. Peterson) will be presented at ANS Winter Meeting, Washington, D. C. November 17-21, 2002.

A series of experiment has been carried to validate the ambient mixing predicted by models. The quasi-steady temperature interface in the stratified ambient, which was predicted by BMIX++ code, has been observed in experiments. The corresponding paper "Forced-Jet Augmentation of Heat Transfer in a Large Stratified Enclosure with a Vertical Cooled Surface"(H. Zhao, F. Niu, and P.F. Peterson) has been completed and presented at the ANS Annual Meeting in Florida.

References

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